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FATIGUE CRACK GROWTH RATE DATA ACQUISITION SYSTEM FOR LINEAR AND NONLINEAR FRACTURE MECHANICS APPLICATIONS

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MARCH 1981

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A computer-based, automated-data-acquisition system was developed for determining fatigue crack growth rate data for both linear and nonlinear fracture mechanics testing. The system hardware employed an HP 9825A Desktop Computer equipped with an HP 6940B Multiprogrammer which digitized the analog test signals (load and displacement) for input to the computer.

For linear elastic fracture mechanics (LEFM) testing the crack growth rate, da/dN, is presented as a function of the stress intensity factor range,

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ΔK. Compliance relationships are used to monitor crack length which is then used to calculate the stress intensity range.

For nonlinear fracture mechanics (NLFM) testing, the crack growth rate is related to the rate of potential energy change, or ΔJ. Compliance techniques are also employed to monitor crack extension.

The results for both analysis methods obtained with the acquisition system are in excellent agreement with results obtained using the more conventional visual and analytical methods. The automated system is superior from a point of speed and consistency, and possesses the accuracy required for valid fatigue crack growth rate (FCGR) testing. Furthermore, the system requires no personal supervision or special specimen preparation and thus would be available for obtaining fatigue crack growth results from test specimens which are subjected to adverse environments which preclude the use of visual measurements.

PREFACE

This interim technical report was submitted by the University of Dayton Research Institute, Dayton, Ohio, under Contract F33615-80-C-5011, "Quick Reaction Evaluation of Materials," with the Materials Laboratory of the Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio.

This effort was conducted during the period of September 1979 through September 1980. The author, Mr. John J. Ruschau, would like to extend special recognition to Mr. Samuel Macy of the University of Dayton whose electronic expertise made this effort possible, and to Dr. Joseph Gallagher, also of the University of Dayton, for his helpful comments and technical review of this paper.

This report was submitted by the author in March 1981.

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SECTION I
INTRODUCTION

Present technology for fatigue crack growth rate (FCGR) testing of materials generally employs visual examination of the specimen surface to determine the crack extension between applied load cycles. Almost all useful FCGR data to date have been obtained in this manner. Such a procedure requires personal supervision, specimen surface preparation for crack tip enhancement, and an adequate optics system (traveling microscope, magnifying glass with reference marks attached to the specimen surface, special lighting, etc.) for accurate crack length measurements. Naturally, the results of the visual procedure hinge on the degree of detail paid to each of the aforementioned elements in the optics system. An ASTM round robin program has determined that the most variability found in FCGR data, obtained from different laboratories, results from the experimental procedures used to obtain the raw test data.[1]

When conducting crack growth rate tests on a material behaving in a nonlinearly elastic manner, the methods employed to collect the raw test data become even more tedious and complex since parameters other than crack length and elapsed cycles must be measured and recorded. Crack tip opening displacement (CTOD),[2] crack tip opening angle (CTOA),[3] and the area under load versus displacement curves[4] represent a few examples of data which are collected and analyzed by investigators to obtain nonlinear fracture parameters. The determination of these parameters are again often subject to operator bias and error, besides demanding constant personal supervision. Data reduction into the final form of crack growth rate versus a crack driving parameter is laborious, often yielding the final conclusions days after actual testing is completed.

Because of such inherent problems in fatigue crack growth testing a completely automated FCGR data acquisition system was

developed to provide a nonvisual method for collecting data, such that it would satisfy ASTM Tentative Standard E647-78T. The system described herein was designed to demonstrate the real-time capabilities of determining the fatigue crack growth rate as a function of either linear elastic fracture mechanics (LEFM) or nonlinear fracture mechanics (NLFM) parameters.

SECTION II
BACKGROUND

Before detailing the FCGR data acquisition system, this section briefly describes the principles of linear and nonlinear fracture mechanics and their respective role in subcritical crack growth under fatigue loading conditions.

1. LEFM APPROACH TO FCGR TESTING

The fundamental assumption of linear elastic fracture mechanics is that for an elastic material containing a crack and some remote stress, the plastic zone at the crack tip must be small relative to both crack size and the material in which it imbedded. When this is true, the stress intensity factor, K, can be used to describe the stress field surrounding the crack tip. For most materials undergoing repetitious loading, slow, subcritical crack growth is controlled by the range of alternating stress intensity. The method for characterizing such crack growth behavior is through fatigue crack growth testing, thoroughly described in ASTM Standard E647-78T.

As previously stated the major source of error in FCGR data can be attributed to the development of the crack length versus load cycles (a versus N) curve, due to the inconsistent random errors in crack length measurements. One method of minimizing this error is to remove the human factor by determining the crack length in some automated manner. Though several methods have been developed, most require specialized equipment not found in most test laboratories. The compliance technique, however, has been recognized for years as a viable approach for indirect crack length measurements, and requires only the monitoring of load and displacement. Because of the ease at which such signals can be interfaced to a computer, it is this method which is used in the acquisition system.

2. J-INTEGRAL APPROACH TO FCGR TESTING

As stated earlier, LEFM principles are valid only if the plastic zone is small. For materials possessing high toughness-to-yield strength ratios, this LEFM assumption can break down and the stresses in the crack tip region might not be adequately described in terms of the stress intensity factor. Different investigators have employed nonlinear fracture mechanics (NLFM) parameters in an attempt to describe the crack tip stress field where the plastic zone becomes large. One NLFM parameter which has received most attention is the energy line integral, J, originally proposed by Rice.[5] For linear elastic materials J is related to the stress intensity factor by:

$$J = \frac{K^2}{E'} \qquad (1)$$

where:

E' = the effective modulus of elasticity, and

K = the stress intensity.

Presented in Figure 1 is one method suggested for defining the J-integral using successive load-displacement curves (increasing portion) of a specimen undergoing cyclic loading. If two successive curves (before and after a crack extension of Δa) are transposed to a common origin as illustrated in Figure 1, the difference in work or pseudo-energy, ΔU, can be obtained simply by measuring the difference in areas underneath the curves up to a constant displacement. For a crack extension of Δa, the value of ΔJ responsible for this crack extension can be determined through the expression:

$$\Delta J = -\frac{1}{B}\left[\frac{\Delta U}{\Delta a}\right]\Bigg|_{\delta \text{ constant}} \qquad (2)$$

where:

B = specimen thickness, and

ΔU = the difference in areas under the load-displacement curves at a constant displacement.

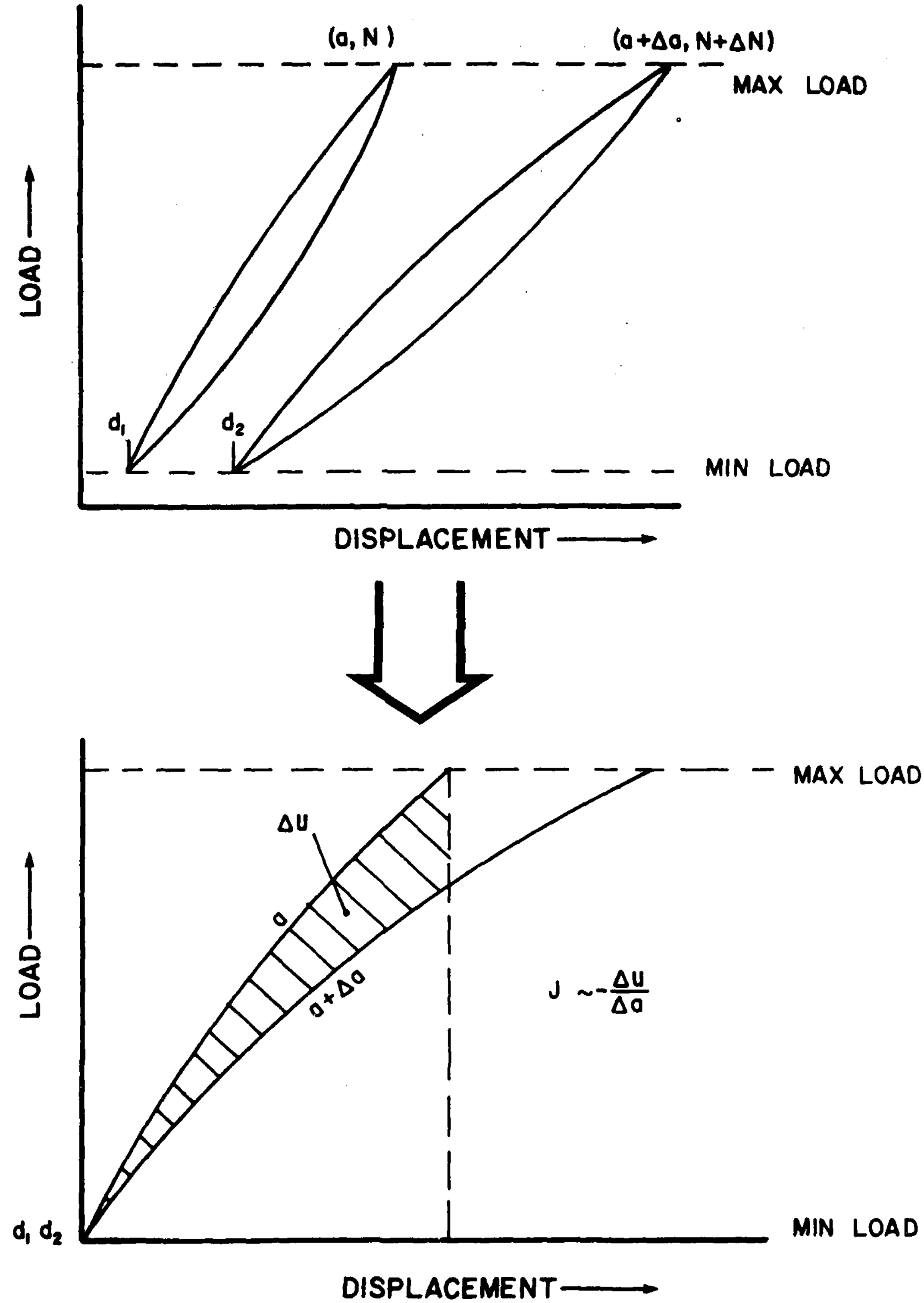

Figure 1. Method for Determining ΔJ During FCGR Testing.

The compliance method for crack length determination, as described earlier, is not entirely applicable for nonlinear type materials since the load-displacement curve is not linear (elastic) over the entire range of loading and may, for some materials/conditions, be nonexistent. However, experience has demonstrated that upon unloading the load-displacement curve exhibits a definable linear region. The ASTM recommended practice for R-curve determination (E561-76T) suggests this unloading behavior can also be used to accurately determine the physical crack length. Thus, the unloading compliance is used herein to obtain the crack length for the NLFM approach.

SECTION III
SYSTEM DESCRIPTION

1. EXPERIMENTAL EQUIPMENT

The acquisition system, illustrated in the schematic in Figure 2, utilizes a Hewlett Packard (HP) 9825A desktop calculator having approximately 25K bytes of internal storage. Accompanying it is an HP 6940B Multiprogrammer which is the device which contains the necessary printed circuit boards required for input/output operations. The multiprogrammer contains two voltage monitor cards which are connected by a unique "Y-cable" option to allow simultaneous readings of two channels; in this case, load and displacement. Each voltage monitor card is capable of measuring bipolar dc voltages in the range of ±10 V, with a least significant bit (LSB) of 5 mV.

A programmable timer card is interfaced to each voltage monitor card to control sampling rate. The period of each time increment is jumper selectable in six decades from 1-4095 μsec to 0.1 to 409.5 sec. Unfortunately, the fastest sampling rate is currently limited by the voltage monitor card conversion speed and, in the manner in which they are used, is roughly 2000 conversions/sec. (Faster A/D converters are presently being procured to replace the voltage monitor cards and should increase sampling rates in excess of 30,000 conversions/sec. Also, because of other test commitments for this equipment the programmable timer is jumpered for 0.01-40.95 sec., limiting the maximum frequency for this demonstration program to ∿1 Hz.)

Additional peripheral equipment to further enhance the system are an HP 9871A impact printer, an HP 7225A plotter, an HP 9885M flexible disk drive unit, and an HP 9878A I/O expander which ties all peripheral devices together.

The test stand to which the acquisition system is interfaced is an MTS electrohydraulic servo-controlled fatigue test machine, capable of cyclic loading up to 30 Hz, with a maximum

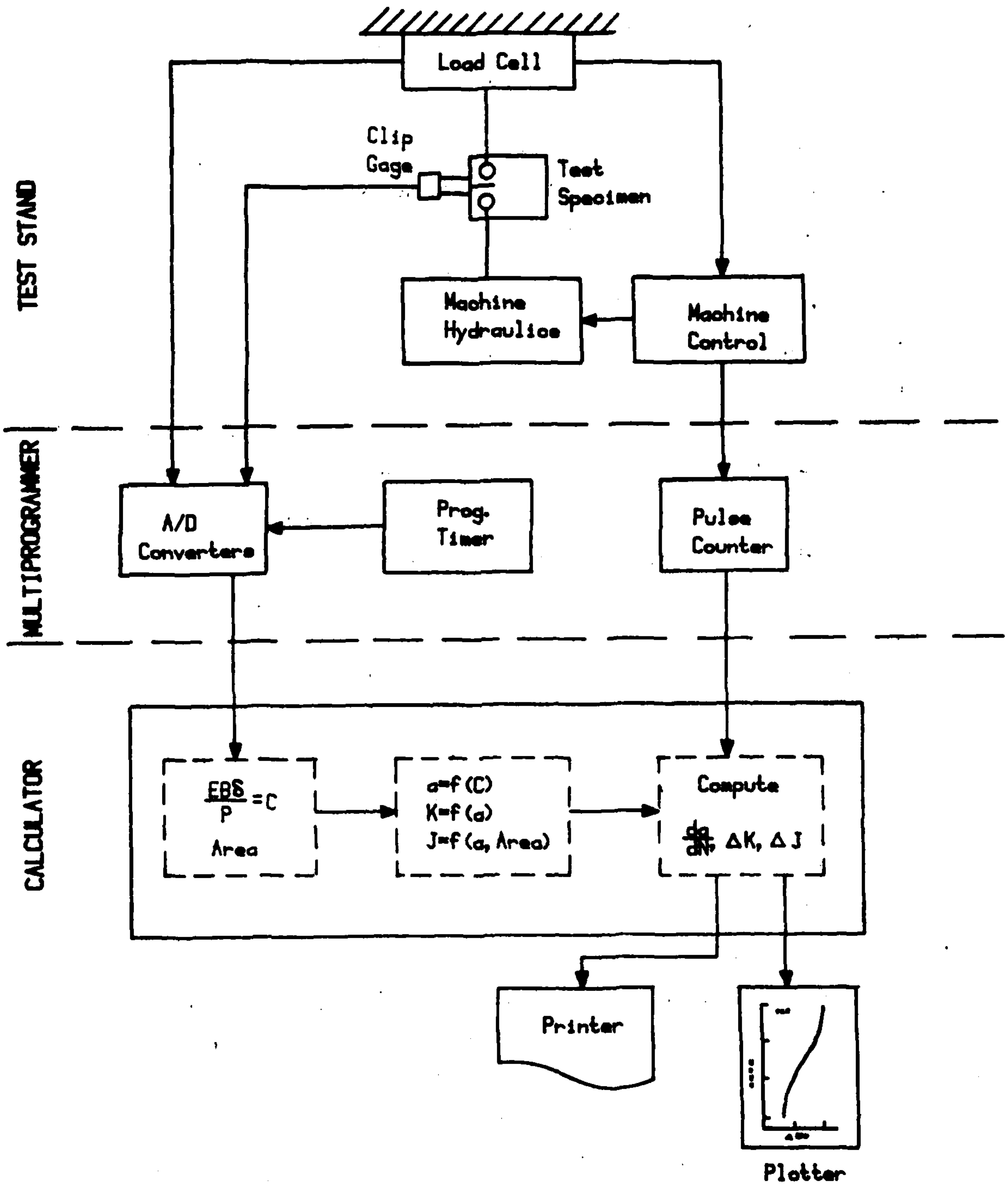

Figure 2. Schematic of FCGR Acquisition System.

load range of ±25 KIP (111 kN). The load signal is obtained by means of a load cell with output voltage range of ±10 VDC. Estimated signal noise level was approximately 7 mV RMS. Displacement is obtained via a clip gage affixed to the specimen and straddling the crack and likewise a ±10 VDC range, with estimated signal noise levels on the order of 2-3 mV RMS. No attempts were made to further filter these load and displacement signals.

2. SPECIMEN GEOMETRY AND MATERIAL

The test specimen geometry for which the system is designed is the compact type, shown in Figure 3, and is one of the two recommended in the present ASTM Standard for FCGR testing, E647-78T. Displacement is measured at the load line by means of the internal machined knife edges as illustrated in Figure 3. (Note: Though this specimen geometry with load-line knife edges is required for NLFM testing, since load-line displacements must be measured, it is not necessary for LEFM testing. For the latter, deflections can be measured at any point for which an accurate compliance expression exists.)

3. SOFTWARE

The system software flow chart is provided in Figure 4. Aside from entering the necessary details (specimen dimensions, load ranges, etc.), the program can be described as three basic routines: (1) a scanning routine which continuously scans the displacement signal until the maximum displacement has changed by some predetermined amount, or a sufficient number of load cycles have elapsed from a previous reading; (2) a reading routine which digitizes the load-displacement waveform; and (3) an analysis routine which analyzes this waveform and determines crack length, the crack growth rate, and either the stress intensity range, ΔK, or the change in J, ΔJ. Each of these routines is thoroughly described in the following sections.

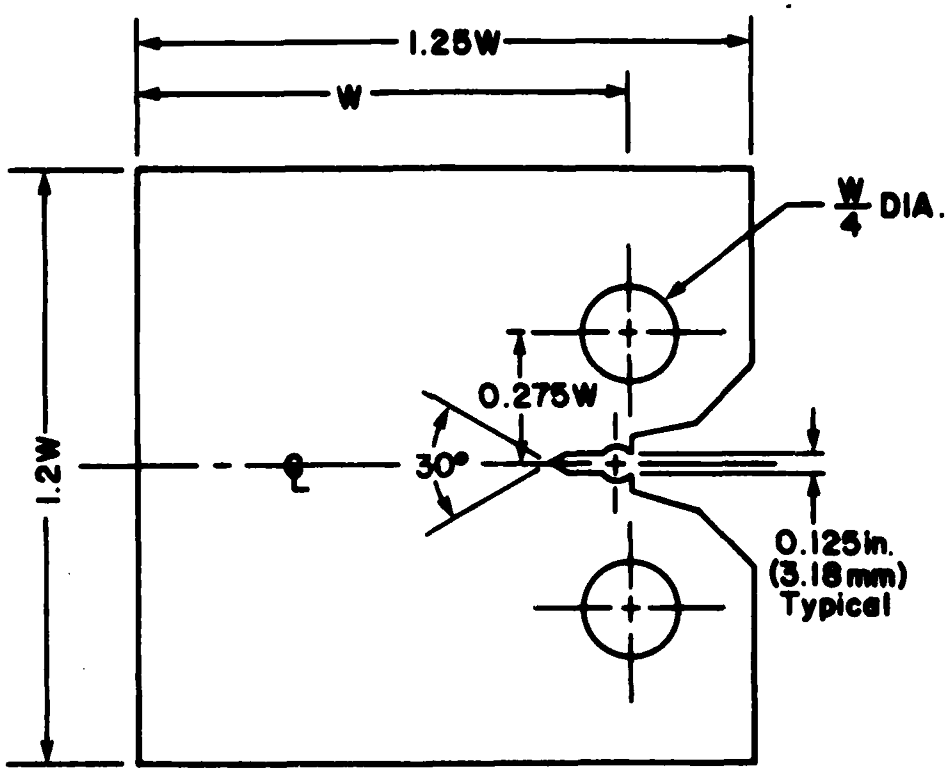

Figure 3. Compact Type (CT) Specimen Geometry.

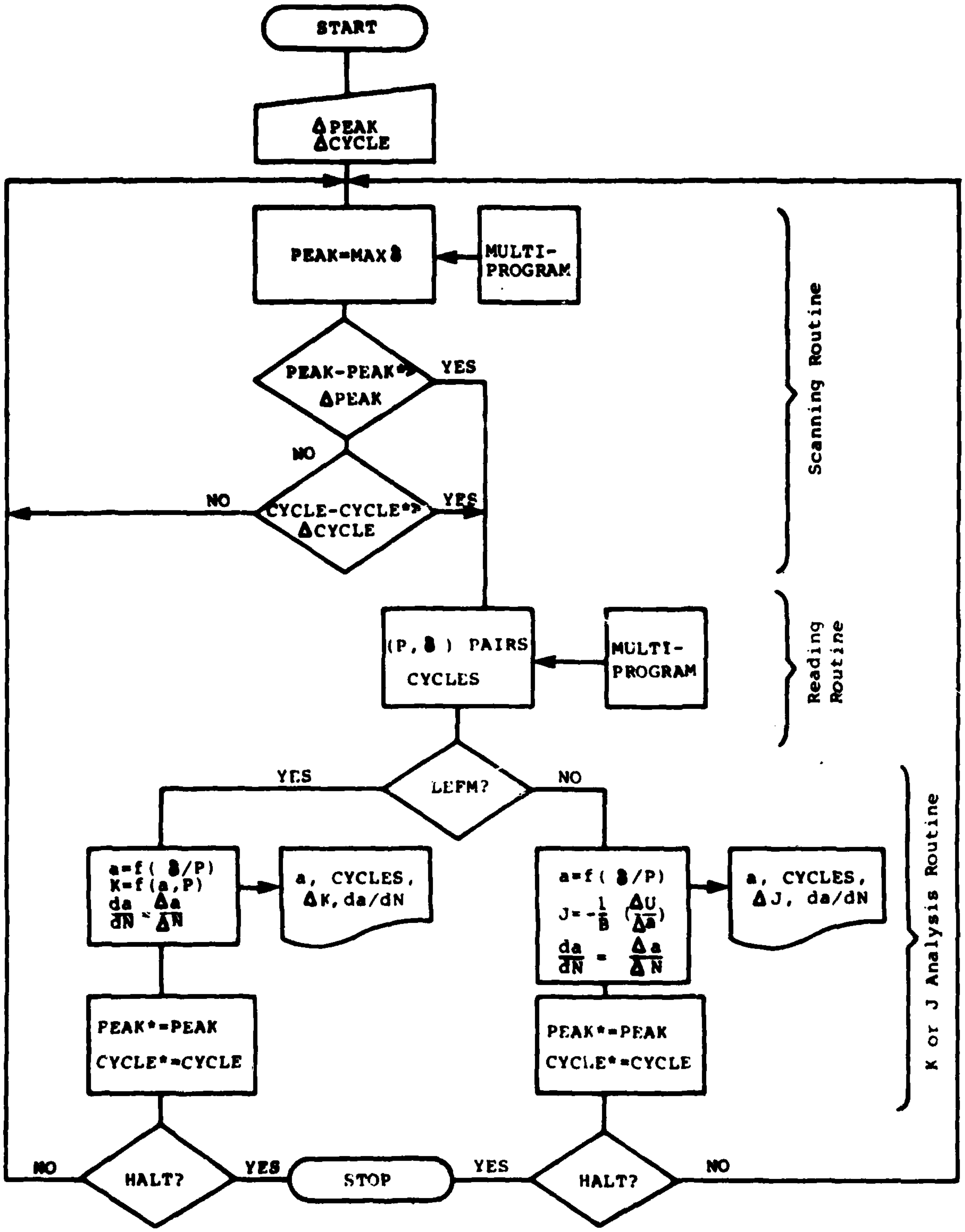

Figure 4. Flow Chart for FCGR Acquisition System.

a. Scanning Routine

Before initiating the fatigue test, certain fixed variables must be entered to provide the basis for subsequent calculations. These include specimen ID and dimensions, load and displacement calibrations (lbf/volt and inches/volt, respectively), material modulus of elasticity, type of analysis desired (K or J), and finally the change in maximum displacement or change in elapsed cycles before a "reading" is taken. After the fixed data are entered, the computer pauses until the fatigue test is initiated.

When the program is continued the calculator begins by digitizing a displacement-time waveform, representing slightly more than one full cycle with a hundred points. These points are then scanned chronologically for the maximum value of displacement. This displacement value is compared to the previous maximum displacement value established at the last reading. If the difference in the maximum values differs by more than that previously specified by the operator (or if it is the first reading), the program goes to the routine to obtain a reading. If the change in displacement is less, the present cycle count is obtained and likewise compared to the last reading. If this change in cycles is greater than that specified by the user, the program goes to the reading routine. If neither of the two conditions are met, the search to obtain the next maximum displacement or cycle count is reinitiated.

b. Reading Routine

When a significant displacement or cycle count change has occurred, a reading is taken in the following manner: simultaneous values of load and displacement are obtained; a hundred load-displacement pairs representing slightly less than two cycles. This is done to insure a minimum and succeeding maximum value. These points are then converted to the proper units of displacement and load and control then transferred to either the K-analysis or the J-analysis routine.

c. Analysis Routine

(1) K-Analysis Routine

If the linear analysis approach was specified, the load-displacement curve is analyzed as follows: the displacement array is scanned for the first minimum value or "valley." Since the load increasing portion consists of approximately 25 points, the first five points (representing 25 percent of the load range) are dropped due to nonlinearities which often exist near the valley of the load-displacement curve. The following ten points are fitted with a straight line using a linear regression analysis to obtain the loading compliance. (Note: Though loading compliance is used in this analysis, it would also be correct to use the unloading compliance, since both are equal, assuming that both crack extension is negligible and that the specimen is not undergoing any time dependent response such as creep during the loading cycle.) The compliance is then used in the following equation[6] to obtain crack lengths in the range of $0.2 \leq a/W \leq 0.975$:

$$a/W = 1.000 - 4.063u + 11.24u^2 - 106.0u^3 + 464.3u^3 - 650.7u^5 \quad (3)$$

where:

$$u = [\sqrt{BEC} + 1]^{-1}$$

and

a = crack length,

W = specimen width,

B = specimen thickness,

E' = elastic modulus, and

C = specimen compliance determined at load-line.

This crack length, along with minimum and maximum loads and specimen dimensions are used to calculate the stress intensity range. Finally, the change in crack length and cycles from the last reading are computed and used to yield the fatigue crack growth rate, da/dN. The secant method for determining crack

growth rate was employed rather than the incremental polynomial method described in the tentative ASTM standard for crack growth rate testing (E647) merely for convenience in demonstrating a real time system such as this. The incremental polynomial method could also have been used but would have significantly increased data reduction time and would not have yielded the instantaneous (real-time) growth rate. Finally, all results are listed and values of da/dN versus ΔK plotted, after which control is transferred back to the scanning routine.

(2) J-Analysis Routine

If the nonlinear analysis approach was specified, control is transferred from the reading routine to the J-analysis routine. In this routine, the displacement array is similarly scanned for the minimum value. Upon determining this minimum point the successive load-displacement points are used to determine the area under the curve. The manner for accomplishing the integration is illustrated in Figure 5.

In integrating the load-displacement curve, two areas are obtained. First, a partial area is obtained over a displacement range exactly equal to the maximum displacement range of the preceding reading (n-1), since the change in areas between two successive readings must be determined over a constant displacement range. The mathematical routine employed to obtain the area is simply:

$$A_n = \sum_{i=2}^{N} (\delta_{i,n} - \delta_{i-1,n}) \times \left(\frac{P_{i,n} + P_{i-1,n}}{2}\right) \qquad (4)$$

where:

A_n = area under the curve of nth cycle,

$\delta_{i,n}$ = ith displacement point, during nth cycle,

$P_{i,n}$ = corresponding load point in the nth cycle, and

N = number of divisions in the load-displacement curve (typically 25).

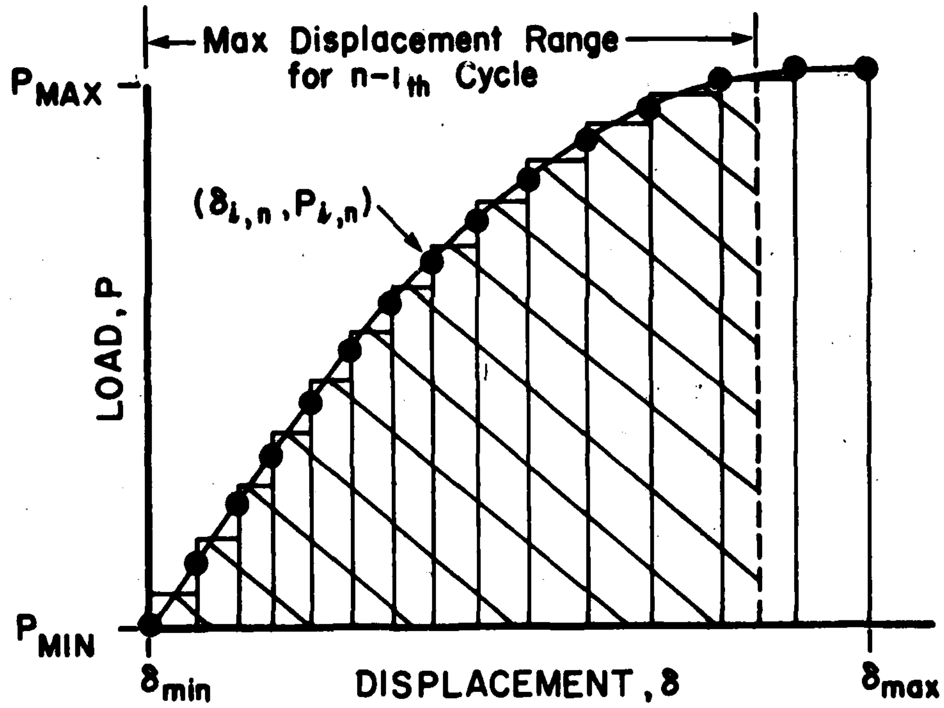

Figure 5. Graphical Method for Determining Area Under Load-Displacement Record for nth Cycle.

The total area calculation is continued up to the maximum value of load. This total area is then stored, along with the corresponding maximum displacement range over which this area was obtained, for comparison with the next (n+1) reading. The partial area (nth) is subtracted from the previously (n-1th) stored total area of the last reading obtained over the identical displacement range to calculate the change in area ΔU, in the manner described in Figure 1.

To determine the crack length, the maximum or "peak" value of the load-displacement curve is established as the starting point for the unloading compliance analysis. The 25 points subsequent to the peak load-displacement value represents the decreasing portion of the load-displacement curve and are analyzed to determine the unloading compliance. Similar to the K-analysis method, the upper 20 percent of the load range is ignored and a straight line fitted in a least-squares method through the next six points. These six points were selected to be above 0.5 P_{max} because of nonlinearities which might exist in the load-displacement curve near the valley resulting from the crack surfaces coming into contact with each other, as well as other phenomenon upon unloading. The unloading compliance is then used in the appropriate compliance equation to yield crack length. By determining the change in crack length and cycle count from the preceding reading, the crack growth rate and ΔJ are computed. Finally, the crack length, cycle count, total area under the curve, crack growth rate, and ΔJ are listed on the line printer and values of da/dN versus ΔJ plotted, after which control is transferred back to the scanning routine.

SECTION IV
RESULTS

Before conducting any crack growth rate testing, certain routines in the acquisition system had to be thoroughly demonstrated for accuracy and precision. These routines include the compliance routine for crack length measurements for both K and J methods, and the integration routine which calculates the area under the load-displacement curve. To accomplish this, a precracked CT specimen, machined from aluminum 7075-T73 plate with a width of 3 inches (76mm), 0.5 inch (12.7mm) thick, was cyclically loaded at 1 Hz. A stress ratio (R) of +0.1 was applied at a sufficiently low maximum stress intensity so as not to cause any significant crack extension over 100 to 200 load cycles. Employing the J-analysis routine, 10 crack length and corresponding area measurements were determined via the acquisition system approximately every 10 cycles and compared to the optically measured crack length (three-point, through-thickness average of crack length measured after test) along with the area obtained from a load versus displacement plot from an X-Y recorder. The reconstructed computer printout, along with the optically measured values of crack length and area, is listed in Table 1. As can be seen the average crack length obtained via the acquisition system is within 0.002 inch (0.051mm) of the visually measured crack length. The precision of the acquisition system is also excellent, as evident by the coefficient of variation (standard deviation/mean) in crack length readings of approximately 0.1 percent. For the area calculation, the average total area under the load-displacement curve obtained via the acquisition system is only slightly less ($\sim$0.7 percent) than the area measured graphically (average of 10 measurements). The reason for the slight bias is not clear, though certainly the accuracy of the X-Y recorder-generated curve must also be considered. Again, the coefficient of variation is minimal, less than 0.3 percent.

TABLE 1

COMPARISON OF ACQUISITION SYSTEM OUTPUT DATA
TO MEASURE CRACK LENGTH AND AREA FOR J-ANALYSIS

Measured crack length = 1.188 inch (30.18mm)
Measured total area = 6.888 lbf-in. (0.778 N-m)

J-Analysis Routine				
Reading No.*	Crack Length inch	(mm)	Total Area lbf-in.	(N-m)
1	1.185	(30.10)	6.839	(0.772)
2	1.185	(30.10)	6.840	(0.773)
3	1.187	(30.15)	6.808	(0.769)
4	1.184	(30.07)	6.850	(0.774)
5	1.185	(30.10)	6.869	(0.776)
6	1.186	(30.12)	6.847	(0.773)
7	1.185	(30.10)	6.813	(0.770)
8	1.187	(30.15)	6.849	(0.774)
9	1.187	(30.15)	6.843	(0.773)
10	1.187	(30.15)	6.850	(0.774)
Avg.	1.186	(30.12)	6.841	(0.773)
Std. Dev.	0.0011	(0.028)	0.018	(0.002)

* Readings taken every 10 cycles.

For the K-analysis routine, the results of a similar verification test are listed in Table 2. For this check, the average crack length obtained via the acquisition system is within 0.001 inch (0.025mm) of the measured crack length with a standard deviation in automated crack length readings of approximately 0.0008 inch (0.02mm).

Having demonstrated that these data taking routines yield sufficient accuracy, a crack growth rate test was initiated on a 3.0 inch (76mm) wide, 0.625 inch (15.9mm) thick, CT specimen machined from aluminum alloy 2124-T851. A sinusoidal waveform with a stress ratio of +0.1 was applied to the specimen at a frequency of 1 Hz. To facilitate rapid data collection, the initial stress intensity range was set at a high level. The change in maximum displacement between crack length readings was set at 0.0005 inch (0.0127mm); the maximum change in cycles was set at 2,500. Uninterrupted crack length measurements were

TABLE 2

COMPARISON OF ACQUISITION SYSTEM OUTPUT DATA TO MEASURE CRACK LENGTH FOR K-ANALYSIS

Measured crack length = 1.191 inch (30.25mm)

K-Analysis Routine		
Reading No.*	Crack Length inch	(mm)
1	1.192	(30.28)
2	1.192	(30.28)
3	1.192	(30.28)
4	1.192	(30.28)
5	1.193	(30.30)
6	1.192	(30.28)
7	1.191	(30.25)
8	1.192	(30.28)
9	1.193	(30.30)
10	1.194	(30.33)
Avg.	1.192	(30.28)
Std. Dev.	0.00082	(0.021)

* Readings taken every 10 cycles.

obtained via a 30X traveling microscope throughout the test for comparison with the acquisition system results.

The test results for the K-analysis method are presented in Figure 6. Note that the results from the visual and automated methods were identical and that data were obtained over a greater range of growth rates with the acquisition system than was achieved by visually monitoring the crack extension due to its faster response at high crack growth rates. The values of crack length versus cycles obtained via computer and visual methods are virtually indistinguishable.

Having proven the linear elastic method successful, the nonlinear, or ΔJ method was employed for a 7075-T73 aluminum CT specimen, 3.0 inch (76mm) wide and 0.5 inch (12.7mm) thick. Though 7075-T73 aluminum does not behave as a nonlinear material, it does have the advantage in that for linear elastic materials

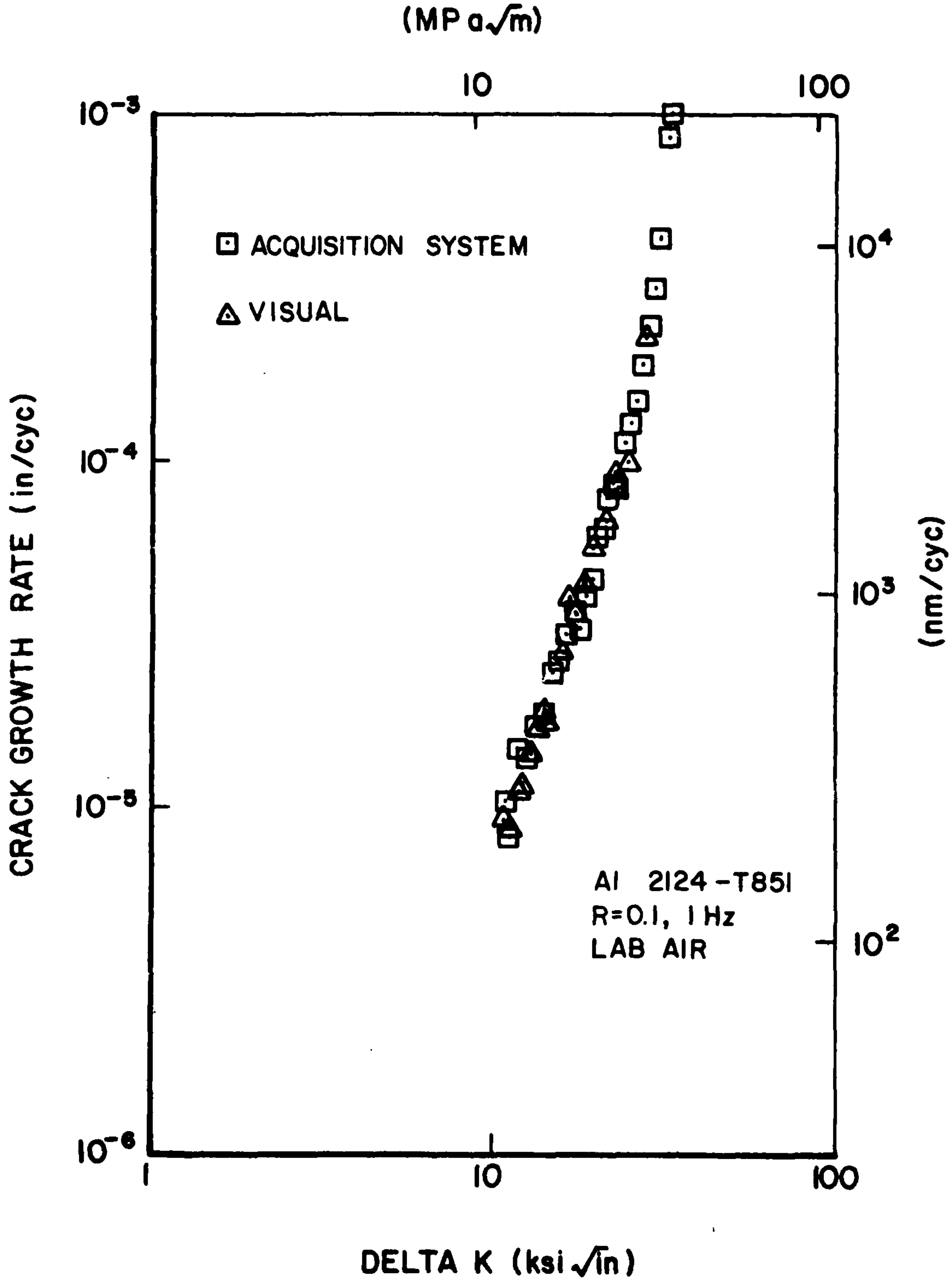

Figure 6. LEFM Crack Growth Data Obtained via Acquisition System and Visual Methods.

the value of J determined is equal to the elastic strain energy release rate, or

$$\Delta J = \frac{\Delta K^2}{E} \tag{5}$$

where ΔK is the stress intensity range, and E is the modulus. Employing this identity as a check for validity, the crack growth was determined as a function of ΔJ and compared to this function of stress intensity calculated over the same interval of crack growth.

The results of this endeavor are presented in Figure 7 (crack growth rate versus ΔJ) for the data generated during a single test. Also shown are the energy values based on ΔK as generated by the system using the compliance crack length. As is evident from the figure, values of ΔJ determined via the acquisition system and the analytical method are in reasonable agreement over the range investigated. A larger scatter, however, exists for the value of ΔJ determined by the computer system versus the analytical values based on stress intensity and elastic modulus. To better estimate the differences between the two data sets, a second degree polynomial was fitted to each set using a least-squares-fit method. Examination of the two curves revealed a difference in ΔJ between each method of less than 5 percent throughout the range of data obtained, and in general, the automated ΔJ values were slightly lower than the analytical results based on K. The source of error or scatter between the acquisition system results and the analytical results are possibly a result of one or both of the following factors.

First, the area calculating routine was demonstrated earlier (Table 1) as possessing sufficient accuracy and precision, the latter evidenced by the small standard deviation of 0.018 lbf-in. (0.002 N-m) for a measured area of approximately 6.84 lbf-in. (0.773 N-m). However, the value of ΔJ is based on the difference in areas between two such records. For

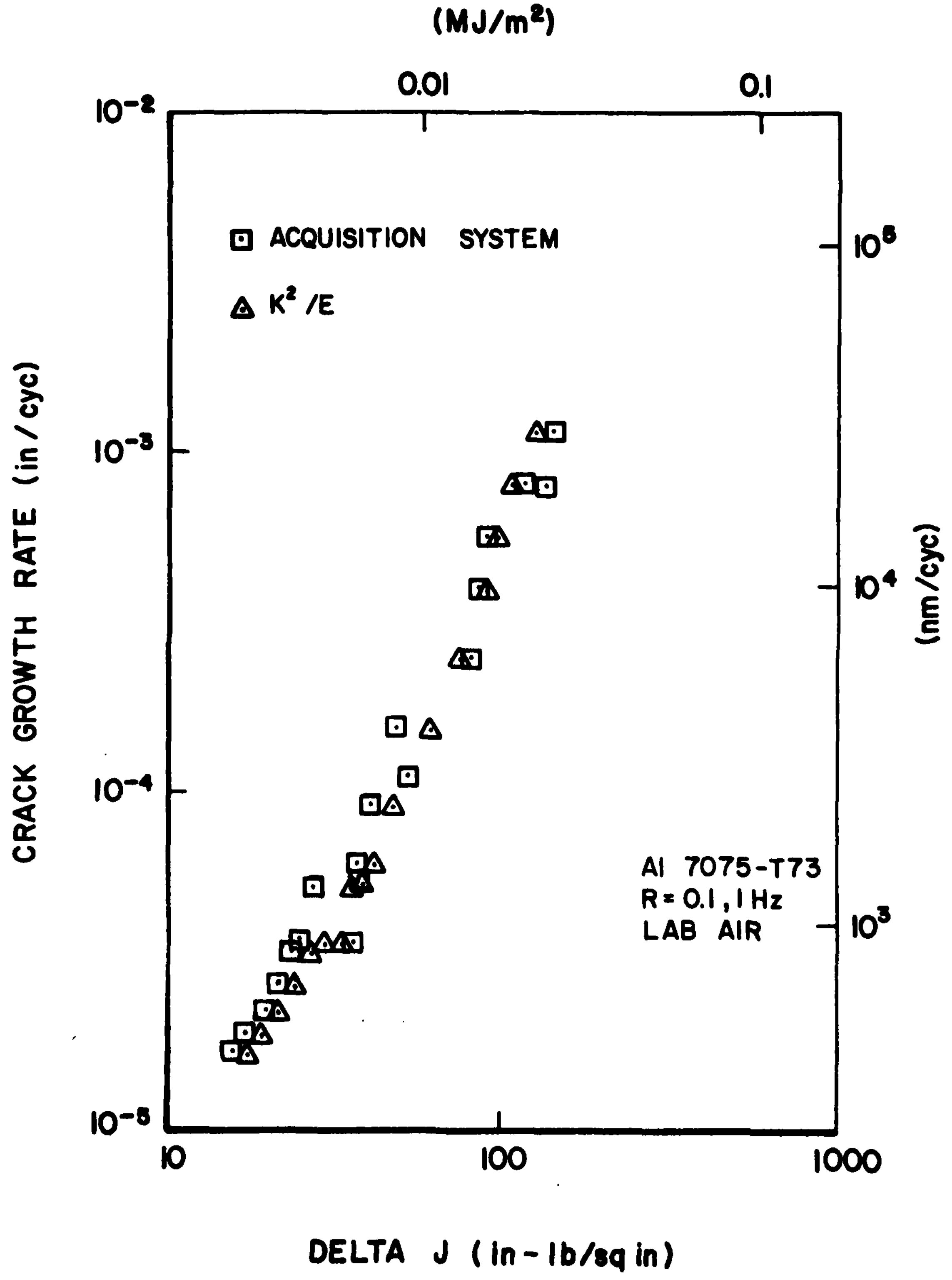

Figure 7. NLFM Crack Growth Data Obtained via Acquisition System and Analytical Methods.

similar test conditions as applied during the earlier verification check, the area difference between two successive readings was on the order of 0.4 to 0.5 lbf-in. (0.045 to 0.056 N-m). Assuming the precision (± 1 standard deviation) remains the same, now a coefficient of variation (standard deviation/avg. area difference) is on the order of 3 to 5 percent. Thus, a seemingly small degree of variation in the total area calculation has a much greater influence on the change in area and subsequently the empirical values of ΔJ.

Secondly, the value of modulus is an important parameter which influences both the compliance crack length and the ΔJ value based on the energy release rate, $\frac{K^2}{E}$. For tests conducted in this program, a handbook value of modulus was chosen at 10.6 msi (73.1 GPa). A 1 or 2 percent error in modulus would create a similar error in both crack length and stress intensity, as well as the analytical expression for ΔJ. Consequently, the difference between the analytic values of ΔJ and the values obtained via the acquisition system might result more from an error in the analytical term and not the automated method.

Finally, as previously stated, the ΔJ data presented in Figure 7 were determined for a linear elastic material. The J-integral method would generally be employed for materials which behave nonlinearly elastic. However, since the routines employed proved quite successful for the elastic material there does not appear any reason why it could not be used for both conditions with equal accuracy.

SECTION V
LIMITATIONS AND OBSERVATIONS

For the conditions investigated in the demonstration tests the acquisition system performed remarkably well, as witnessed by results just presented. When utilizing such a system over a broad range of test conditions a number of limitations become obvious in both the specific system described and in some general techniques employed.

First, when performing on-line data reduction with a single-task computer system, computer processing time becomes a limiting factor since during such data reduction the experiment must go unmonitored. For the K-analysis routine the time required to digitize a single load-displacement waveform, convert to proper units, and determine crack length takes roughly 3 seconds, allowing anywhere from a few to a few hundred cycles to elapse, depending on test frequency. For ΔJ determination, the data reduction time is typically 50 to 75 percent greater. Thus, at high test frequencies and high growth rates, the crack extension interval, Δa, might become too large to yield valid growth rate data. If, in a specific example, the desired crack measurement interval for the K-analysis is 0.010 inch (0.25mm) [the minimum interval recommended in E647] at a test frequency of 30 Hz, the maximum crack growth rate the system would be capable of responding to is about 10^{-4} in/cyc (2×10^{-3} mm/cyc). Above this growth rate, the minimal measurement interval the system could record would increase. To record growth rates up to 10^{-3} in/cyc (2×10^{-2} mm/cyc) maintaining the same measurement interval would require reducing test frequency to about 3 Hz. Thus the maximum usable cyclic rate of the system is dependent on crack measurement interval and the maximum desired range of crack growth rate. The only method to significantly reduce this limitation, yet keeping the same hardware, would be to convert from an on-line acquisition system to a system which would only store the significant cycles during test and do the data reduction after

testing is completed. This would reduce the elapsed time between readings by about 60 percent for the K-analysis routine and 80 percent for the J-analysis routine.

Secondly, because computer storage size was a restriction, crack length measurements and ΔJ estimations are determined from a single load-displacement record and thus subject to a greater degree of scatter than if an averaging technique were used. Hardware modifications are presently underway to increase the internal storage size from 25K to 64K, allowing several sequential load-displacement cycles to be averaged. By determining, for example, five compliance values for five sequential cycles, disregarding the lowest and highest values and averaging the remaining three, scatter in crack length readings can be further reduced.

A third point which must be considered in a system such as this is the resolution of the displacement transducer system used to obtain compliance measurements and thereby crack length. Since at the beginning of a typical crack growth test (i.e., $a/W=0.2$) the maximum displacement might be 5 to 10 percent of the total range required for larger crack length measurements ($a/W=0.8$) the resolution at the beginning of the test is inherently inferior to that near test completion. A solution to this limitation is to change displacement ranges during the test automatically, thereby maintaining a high resolution throughout the entire test. A multiple relay card will soon be installed in the multiprogrammer system enabling the computer to change displacement ranges without interrupting the fatigue test.

SECTION VI
CONCLUSIONS

The following conclusions are based on the fatigue crack growth results presented herein for aluminum alloy 2124-T851 and 7075-T73. For both linear and nonlinear methods, the results obtained by the acquisition system were compared to the more conventional visual and/or analytical methods.

1. Fatigue crack growth rate data obtained via the acquisition system for the LEFM approach are identical to those obtained using the conventional visual methods.

2. The crack growth data obtained via the acquisition system using the NLFM (or ΔJ) method of analysis exhibited a difference within 5 percent between the system determined ΔJ values and the theoretical values of ΔJ based on the strain energy release rate.

3. For both methods used, the compliance crack length values accurately predicted the visual readings; less than 0.1 percent difference for the LEFM routine, while for the NLFM, an average difference observed was less than 0.2 percent.

4. The proposed data acquisition system is superior to any of the conventional methods used today, requiring no special specimen surface preparation, no personal supervision, and yielding immediate, accurate, and consistent results which are insensitive to any operator bias. A system such as this can be used to obtain valuable data where visual readings are impractical or impossible.

5. With the ability to accurately determine the stress intensity during testing, a simple modification to the system can be made by the installation of an analog-to-digital (D/A) output card, enabling stress intensity controlled testing.

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